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Two types of radio galaxies: a new approach

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Abstract. We do not fully understand the dynamics and evolution of a radio galaxy. Models of classical double (Type II) sources are in a reasonable state, but these objects are rare. Non-type II sources (generically called Type I) are far more common, but much less well understood. In this paper I use the data to suggest possible new models for Type I sources, and discuss the physical questions which these new models raise.

1. Introduction

What is a Type I radio source? This question can be answered in terms of the data (what does it look like?), or in terms of the dynamics (how does it work?). In neither case is the answer clear. The observational answer has changed over the years. The initial Fanaroff-Riley definition combined morphology (inner hot spots, close to the galaxy) with low radio power (P_{rad}). Later, Ledlow and Owen (1996) complicated the issue by showing that the division in P_{rad} between Types I and II depends on the luminosity of the parent galaxy, L_{opt}. Now, with the advent of large radio samples, it has become clear that the morphology issue is also more complicated than was initially realized. When we study images of radio galaxies which do not have strong outer hot spots (that is, which would not be called Type II), we soon discover these sources are not a uniform set.

The dynamical definition of a Type I is equally unclear. We can pose several questions which should be answered by a dynamical model of radio sources. How does a given source evolve? What governs its size, morphology, and radio power? How do these quantities change with age? We have a reasonable picture for Type II sources, which in principle allows quantitative answers to these questions. We do not, however, have a similarly useful picture for non-Type II sources, even though they constitute most of the radio source population. This is my concern in this paper. As a shorthand, I will refer to any source which is not clearly a Type II, as a Type I. In what follows I will discuss the morphology and dynamics of these interesting sources, combining the material from my talk and poster.

2. Dynamical Models: Type II sources

Classical double sources have inspired quite a bit of study. As a result, we have a fairly good picture of their dynamics. A collimated, supersonic jet (with initial velocity v_j, carrying momentum flux Π_j and energy flux P_j) is driven out from the galactic core. It propagates into the ambient gas at a rate determined by its momentum flux, cross sectional area A and the density of the ambient gas, ρ_x (eg, Scheuer 1974). One way to write this is

$$\Pi_j = \rho_x A \left(\frac{dD}{dt} \right)^2 \tag{1}$$

noting that $\Pi_j \simeq P_j / v_j$, and D is the length of the jet. The resultant propagation speed, dD/dt, is subsonic relative to the jet material, so that the jet plasma passes through a terminal shock (identified with the hot spots). The post-shock jet plasma collects in a lobe/cocoon; much of the energy carried out in the jet ends up stored in this lobe. The lobe development is governed primarily by energy conservation (e.g., Eilek & Shore 1989):

$$\frac{dE}{dt} = P_j - p \frac{dV}{dt} \tag{2}$$

if E, p and V are the internal energy, pressure and volume of the lobe. It is important to note here that the lobe and jet must be treated separately; the large volume of the lobe is needed to store the energy ($\int P_j dt$) which has been carried out by the jet over the lifetime of the source. This simple model is of course modified in detail by such effects as shocks in the ambient gas, or flows and turbulence in the lobe, but the global picture should still be accurate. This picture has been revisited by several groups lately (eg, Daly 1994; Kaiser, Dennett-Thorpe & Alexander, 1997; Blundell, Rawlings & Willott, 1999).

3. What about Type I sources?

The situation is not nearly as good for Type I sources. The idea arose in early work that Type I sources are turbulent, entraining plumes (eg, De Young 1981, Bicknell 1986). This picture was initially attractive, and did seem a good guess for the few sources which had been well studied at that point, such as 3C31. Various authors developed detailed models based on this cartoon, assuming a steady, one-dimensional flow, and attempted to quantify flow speeds, mass entrainment rates, or spectral aging.[1] However, with more data it is becoming clear that these models do not tell the entire story. Three clues are pointing us toward the true situation.

One clue comes simply from the appearance of high-quality images. Examples include the tailed sources imaged by O'Donoghue, Owen & Eilek (1990). The sources often show complex internal structures –filaments – aligned with the overall flow. They can show sudden, dramatic changes in the flow, changing in a few kpc from a well-collimated jet to a broader, poorly collimated tail. These common features do not seem related to terrestrial examples of subsonic, turbulent plumes (although it may be that turbulent flows of a magnetized plasma

[1] Much of this modelling has addressed only the inner regions of the sources, where the jets are bright enough to be well imaged, and thus has not considered more global questions such as the growth or evolution of the entire source.

in the complex atmosphere surrounding a radio galaxy may lead to such structures). Sources which appear easily to fit the turbulent-plume picture, such as 3C31, turn out to be rare (cf. Parma et al 1999, or Owen & Ledlow 1997).

Another clue comes from spectral index imaging. Examples include 3C449 (Katz-Stone & Rudnick 1996), 3C465 (Owen & Eilek unpublished), and two tailed sources imaged by Katz-Stone et al (1999). These data clearly reveal two-dimensional structure, in which flat-spectrum "jets" can be found within steep-spectrum "tails" or "sheaths". As flatter spectra are associated with some combination of younger plasma and higher magnetic fields, these images suggest that much more is taking place than simple, one-dimensional turbulent flow.

A third clue comes from trying to apply equations (1) and (2) to a turbulent-plume model (Eilek, unpublished). Successful use of these equations (with reasonable estimates of jet power and speed) requires the energy-storage volume to be much larger than that of the propagating jet. This is, however, inconsistent with existing models of turbulent plumes. While such simple modelling is clearly less robust than good data, this result again suggests that a Type I "tail" is better modelled as two-dimensional , with a "core" and a "sheath".

4. Type I sources: What do the Data Tell Us?

In my opinion, we are far from a clear understanding of how Type I sources work. To gain insight, my colleagues and I have been working with a new data set, the Ledlow-Owen sample of radio sources in Abell clusters. We initially expected that the evolution of a source would be determined by such factors as its jet power, parent galaxy size, or the density and pressure of the surrounding medium. To test these ideas, we gathered radio data (power and flux size), optical data (parent galaxy magnitude) and X-ray data (from the ROSAT All-Sky Survey for a subset of the sample; to obtain projected distance from X-ray peak and estimated cluster gas density local to the radio source). The data and results are summarized in Eilek et al (2000), and will be presented in more detail in Eilek et al (2001, in preparation).

My particular role in this project was to measure the flux sizes of each of the sources, and (with a grad student, T. Markovic) to determine the source's relation to the X-ray peak (which is a good measure of the dynamical center of the cluster). Working individually with images over 200 sources taught me a great deal about the nature of the sources, and led me to an unexpected conclusion. That is: although almost all of these sources would be Type I based on their (P_{rad}, L_{opt}) values, they are clearly not a uniform set. Of the 197 sources which were well-enough resolved to estimate their structure, 188 could easily be put into one of two classes. Our classification criterion is, *how far does the jet propagate undisturbed?* An example of each class is shown in Figure 1. The two classes are as follows.

- **Straight sources** comprise about 1/3 of the set. In these sources, the jet retains its identity all the way to the outer end of the source, where it may or may not end in an outer bright spot. The end of the flow (what might be called a working surface) is apparent in most of the images. The jet is generally embedded in a lobe or cocoon (although this may be hard to

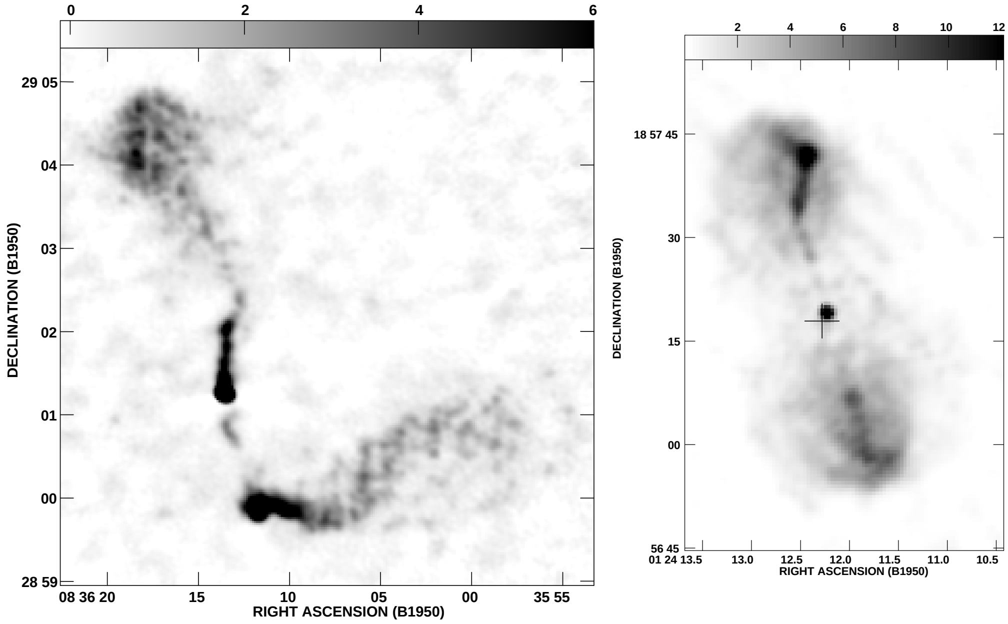

Figure 1. Left, 0836+290, an example of a tailed source. The transition from a narrow inner jet, through an interior hot spot, to a tailed flow, is apparent. Right, 0124+189, an example of a straight source. The inner jet can be seen within each lobe; the jet in the north lobe stays brighter and forms a weak hot spot.

detect in some of the fainter sources, leading to what others have called a "naked jet"). The sources as a class are not strongly bent; the degree of jet collimation varies across the class. Classical Type II sources fall into this category; there are 13 of them in the Ledlow-Owen sample.

- **Tailed sources** comprise about 2/3 of the set. In these sources, the jet begins narrow and well-collimated. It soon undergoes a dramatic transition at an inner hot spot, where the flow becomes broader and brighter. High-resolution images show complex structure within these hot spots. The flow does not fully disrupt at the hot spot, but continues on into a radio tail. In some sources the end of the tail can be seen (at low frequencies), while in others the surface brightness fades too fast to allow detection of the end. Sources which have been called Wide-Angle or Narrow-Angle Tails fall into this category. However, a large number of these sources do not bend at the hot spots; bending is not a defining property of the group.

This morphological division correlates nicely with the work of Parma et al (1999). They found that Type I sources (from the B2 sample) divide into two spectral types: those in which the spectrum steepens going away from the core, and those in which it flattens. Based on available spectral information (usually one-dimensional; for instance from O'Donoghue etal 1990, or comparing the sources used by Parma et al), we find that that Parma et al have identified the same groups. Tailed sources tend to have spectral steepening outwards, away from the (interior) jet/tail transition, while straight sources tend to have spectra steepening inwards, away from the (exterior) end of the flow.

What determines whether a given radio galaxy will be Straight or Tailed? We were disappointed to find no correlation between the two classes and anything we have been able to measure (Eilek et al 2000). The two classes do not differ in radio power; thus they do not differ in underlying jet power, unless the conversion efficiency to radio power is quite different in the two classes. They do not differ significantly in local gas density, offset from the cluster X-ray center, or magnitude of the parent galaxy. They do not differ in radio size, so the difference between them is unlikely to be due to one evolving into the other. There is no evidence of unusual conditions in the ambient cluster gas (such as a discontinuity) at the hot spots in the Tailed sources. It follows that there must be an internal discriminant, such as jet density, velocity or magnetic field, which determines the nature of the source. I expand on this in §5.3.

To close this section, I note that the radio sources in the Ledlow-Owen sample are representative of the general (nearby) radio source population. The fact that they lie in Abell clusters does not make them atypical. For instance, Miller et al (1999) worked with a set of nearby radio galaxies (both Types I and II) not in Abell clusters. They combined optical and radio data to show that the sources lie in a low-richness extension of the Abell clusters (with some tendency for Type I's to be more frequently associated with extended X-ray emission). Also, Ledlow, Owen & Eilek (2000) compared optical and radio properties of the Ledlow-Owen sources (within Abell clusters) to those of a set of B2 and Wall-Peacock sources (not within Abell clusters). They found no significant differences between the two sets in optical or radio properties. Thus, there seems to be no ground for considering radio sources in Abell clusters to be unusual. Conclusions drawn from them can safely be extrapolated to the general population.

5. Type I Sources: What of the Physics?

In the previous section I argued that Type I radio galaxies can be divided into two classes, Straight and Tailed, based on their morphology. This new view leads us to new physical questions which must be posed (and eventually answered). Three questions occur to me, for which I offer answers of varying robustness.

5.1. What picture might work for the Straight sources?

I suspect that all Straight sources can be modelled in terms of their global evolution just as classical doubles are. In fact, classical doubles can be viewed simply as a subset of this group. That is, all of these sources obey momentum and energy conservation through their length and lobe volume, as described in §2. If this is the case, then their modelling should be straightforward. Predictions such as evolution in the (P_{rad}, D) plane can be made and tested much as has been done for Type II's. Details of the predictions, particularly the luminosity, will need to be modified for those Straight sources with less well-collimated jets and fainter, or absent, exterior hot spots. The embedded jets in these sources are very likely to be flatter spectrum than the lobes which surround them (although I am not aware of two-dimensional spectral imaging on any non-Type II straight sources).

5.2. What picture might work for the Tailed sources?

I also suspect that Tailed sources involve more complicated flows. The transition from jet to tail, which defines these sources, is very suggestive of an instability which suddenly grows and saturates. Spectral data suggests that these tails also have a two-dimensional, jet-plus-sheath, structure. Models similar to those proposed for Straight sources may be the place to begin. However, the development of these sources may be more sensitive to external conditions than is the case for the straight ones. Possible complications are flows in the ambient medium, turbulence and mixing, and bouyancy. Note that Tailed sources which bend, usually do so at the hot spot. Flows in the ambient medium may be responsibile for the bending and may also extend the length of the tail. Note, also, the broader, "cap-like" ends which can be seen in some tailed sources are reminiscent of neutral buoyancy flows (e.g., Churazov etal 2000, in a different context). The wide range of behavior found in this group, from unbent sources to Narrow-Angle Tails, may make this set difficult to treat uniformly or statistically. Case studies of several individual sources may be more profitable here.

5.3. Why are there two types of Type I's?

My colleagues and I were unable to find any measured quantity (radio, optical or X-ray) which discriminates between Tailed and Straight sources. If the answer is not in something we can measure, it must be in something we cannot measure. That is, there must be an internal variable which differs between the two classes. If the Tailed sources are the result of an instability which suddenly grows and then saturates, then the difference between the two classes must be the onset, or not, of this instability. It would follow that all sources start life looking "straight", that is, with a jet propagating into the local ambient medium, depositing a cocoon as it goes. If the jet is unstable, nonlinear growth sets in before the jet has gone further than several tens of kpc, and the post-instability flow gives the source a Tailed morphology. If the jet is stable, it continues as it has been, growing in length and leaving excess jet material behind in a lobe.

It remains is to determine what sets off the instability. If we consider a Kelvin-Helmholtz type of instability, we know from analytic and numerical methods (e.g., Rosen et al 1999 and references therein) that it is sensitive to the density, speed and magnetic field of the flow (see Eilek et al 2000 for more discussion). A change in any of these quantities (for instance as the jet expands or the cocoon evolves) has the potential to set off the instability. It also remains to determine whether such an instability can grow and saturate quickly enough to reproduce the hot spots we observe. This is probably best tested by numerical simulations; until such time this saturated-instability model is only a cartoon.

6. Caveats on Spectral Aging

One important application of a dynamical model of radio source evolution is to the interpretation of spectral data. Spectral steepening is commonly interpreted as arising from aging of the electron population due to synchrotron losses. It has often been used as a measure of the age of a radio source. Several authors have carried out such analyses for Type II sources (e.g., Leahy, Muxlow & Stephens 1989, Carilli et al 1991) and a few have done so for Type I's (e.g., Parma et al 1999). If we have a good dynamical model of a radio source, we can (in principle, anyway) determine both its physical age and the internal distribution of its magnetic field with some confidence. We can then use this information to track the emission history of the relativistic electrons, and thus test the hypothesis that the spectral steepening is due to electron aging.

In practice, of course, such analyses are hampered by necessary but probably unsupported assumptions. Examples of this include assumptions about the magnetic field behavior, about the shape of the spectrum (which must be inferred from a small number of frequencies), or about the relation between hot spot equipartion pressure and jet thrust (see also comments by Blundell & Rawlings 2000). A further complication is now apparent: the sources are multi-dimensional. That is, neither surface brightness *nor spectrum* can be described as one-dimensional functions of distance away from the hot spot (whether inner or outer). This is true to some extent of Type II sources (e.g., Leahy et al 1989), and is particularly true of Type I sources (such as those mentioned in §3). The two-dimensional complexity of the spectral images can vitiate conclusions based on a one-dimensional "slice" analysis. As an example (illustrated by data in Katz-Stone et al 1999), consider a tailed source in which flat and steep spectrum components coexist. If the relative mix of these two components changes, such as the steep spectrum component suddenly becoming brighter, a "slice" analysis will erroneously conclude that the flow has suddenly decelerated – when this is not at all the true situation.

7. Conclusions

All I can really conclude is that Type I sources remain a fascinating challenge to our understanding of radio galaxy evolution. I anticipate that combining high-quality imaging with new theoretical analysis will improve our understanding, and no doubt expose the naivety of my speculations here.

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